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DEPARTURE ENERGIES, TRIP TIMES AND ENTRY SPEEDS FOR HUMAN MARS MISSIONS

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The study examines how the mission design variables departure energy, entry speed, and trip time vary for round-trip conjunction-class Mars missions. These three parameters must be balanced in order to produce a mission that is acceptable in terms of mass, cost, and risk. For the analysis, a simple, massless-planet trajectory program was employed. The premise of this work is that if the trans-Mars and trans-Earth injection stages are designed for the most stringent opportunity in the energy cycle, then there is extra energy capability in the "easier" opportunities which can be used to decrease the planetary entry speed, or shorten the trip time. Both of these effects are desirable for a human exploration program.

INTRODUCTION

The Exploration Office at NASA's Johnson Space Center (JSC) is responsible for leading architecture studies to identify candidate methods and technologies for sending humans to Mars. In fulfilling this role, the Exploration Office must set the groundrules for the mission studies conducted jointly at many NASA centers. Three of the fundamental inputs for these types of architcture-level studies are interplanetary trip times, maximum planetary departure energies, and maximum entry speeds.

This paper summarizes a study to determine how the mission design variables *departure energy*, *entry speed*, and *trip time* vary for round-trip conjunction-class Mars missions. These three parameters must be balanced in order to produce a mission that is acceptable in terms of mass, cost, and risk. Long-term program evolution and technology investments are also important factors to consider. The objective of the study was to determine what minimum entry speeds could result, both at Mars and at Earth, if the major propulsive stages were designed to be adequate for all mission opportunities, and what the resulting trip times would be. With this investigation, three questions were addressed, each of which are discussed in detail below.

(1) What are the advantages of designing the in-space transportation elements to satisfy any Mars mission opportunity?
(2) For what Mars and Earth entry speeds should the aeroshells be designed?
(3) How long are the trip times for the interplanetary transfers?

The first question addresses designing the mission transportation elements to satisfy all opportunities in the synodic energy cycle. As illustrated in Figure 1, for a constant trip time, it takes a different amount of energy to leave Earth and reach Mars, and to leave Mars and reach Earth, on each opportunity. This is due to the eccentricity and inclination of Mars' orbit. The energy variation is cyclic, repeating about every 15 years, or 7-8 opportunities. The time period considered in this study includes the Mars mission opportunities in 2009 through 2028. This period spans a full energy cycle, and gives insight into the preceding and following cycles. The amount of energy required determines the masses, volumes, and fuel required for the trans-Mars injection (TMI) and trans-Earth injection (TEI) stages. Intuitively, the hardware designed for a human Mars mission should be robust enough to succeed in any given mission opportunity, in case of a missed launch. In other words, if a launch is planned for 2011 and technical problems on the launch pad delay the launch beyond the injection window, the hardware should be designed to perform the mission, with the same payload, 26 months later. The disadvantage is, in the years that require less-energetic transfers, a mass penalty is paid for using the bigger propulsion stages. On the other hand, it is less costly to design two stages, one for TMI and one for TEI, and to use those stages repeatedly. The key metric is the mass penalty for designing the injection stages for the most energetic opportunities, then using those stages in every opportunity for commonality and reduced cost.

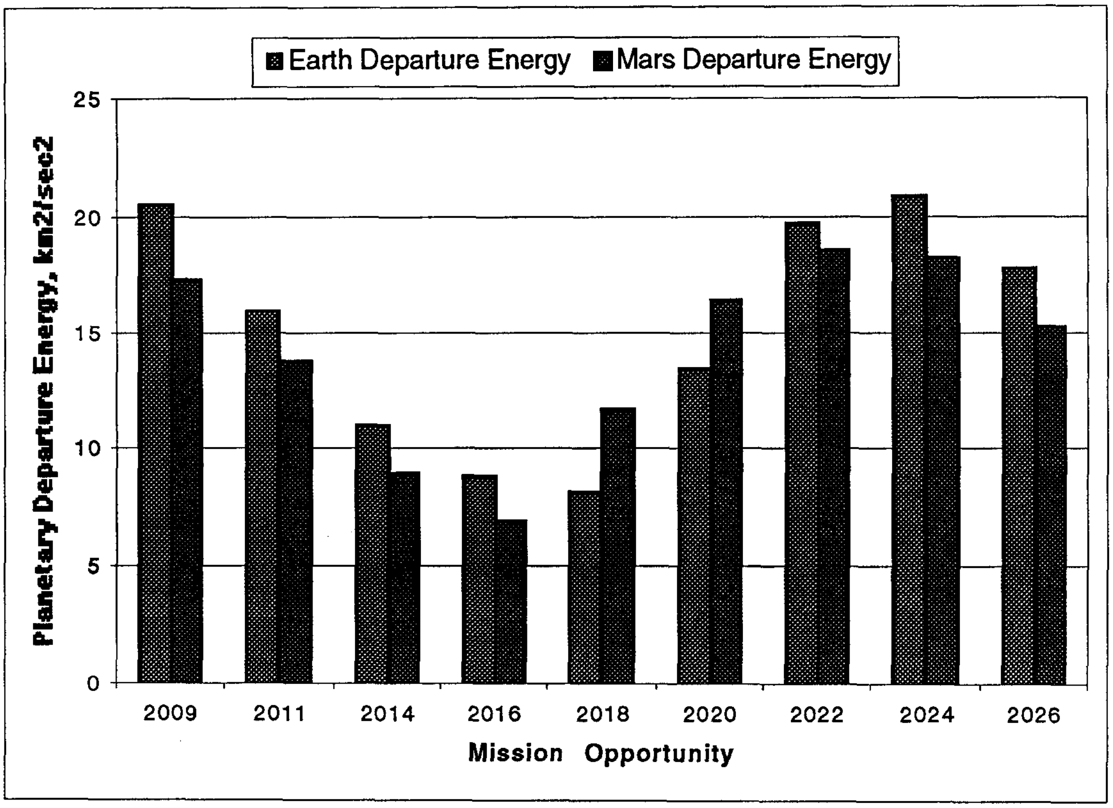

Figure 1 Variation of Departure Energy with Mission Opportunity, for Earth-to-Mars and Mars-to-Earth Trajectories

The second question is what entry speed to use in designing aeroshells for atmospheric encounters. The majority of the human Mars mission studies assume that aerocapture will be used for Mars orbit insertion instead of propulsive capture. This eliminates the mass associated with bringing large amounts of propellant for slowing down to capture into a Mars parking orbit. Back at Earth, the crew will either enter directly in an Apollo-type capsule from their hyperbolic orbit, or they will be aerocaptured into a low Earth orbit for retrieval. For all missions, the vehicles will need sufficient structure and thermal protection system (TPS) materials to survive atmospheric maneuvers. Like departure energy, the planetary entry speed varies, for a given trip time, with each mission opportunity. The issue of choosing an entry speed combines several factors and affects many aspects of the vehicle. Most obviously, it drives the thickness of the TPS, which translates into vehicle mass; i.e., if the entry speed is very high, the heating environment will be more severe, and more material will be required. To look at the problem another way, if the desire is to eliminate the extra mass, more advanced, lightweight TPS materials will have to be developed, so the cost of the vehicle will increase. Entry speed also has a large effect on the width of the flight corridor, which is especially critical for aerocapture. If the flight path angle at entry interface is highly constrained, that increases navigation accuracy requirements and the amount of control authority required during the various atmospheric flight phases. Both of these add to mission cost. Moreover, there is increased risk in flying through a relatively unknown environment within highly-constrained parameters.

A third question is how long the crew should be expected to spend on an interplanetary transfer. The philosophy of mission designers so far has been to limit the amount of time in zero-gravity as much as possible, and assume that the 500 days in the one-third-gravity environment of Mars will have less debilitating effects. Again, the trip time varies, for a given departure energy, across opportunities. Also, as the trip time increases, the energy requirement and the entry speed generally decrease, up to a point. So, longer trips are better, from the perspective of mass and perhaps vehicle cost, but how long is too long for the crew? Thus far, NASA's mission designers have tried to keep each leg of the journey below 180 days. This "benchmark" of about 6 months was established when American astronaut Shannon Lucid spent 182 days in space, although Russian cosmonauts have spent up to 365 consecutive days in space.[1] The effects on humans of another 10 to 40 days on each leg of the Mars mission has not been quantified. Furthermore, no human has any experience with spending six months in zero-g, 18 months in one-third-g, and then six months in zero-g, only to return to 1-g. Long-term experience aboard the International Space Station will increase understanding of the zero-g issue, and lead to improved microgravity countermeasure developments. The other concern with long in-space transits is that of radiation exposure. Once outside the Earth's magnetosphere, crewmembers and their sensitive equipment have nothing to protect them except the walls of their craft. Clever vehicle designers have concepts for "storm shelters" surrounded by water and food inside transit habitats, but radiation protection and hardening will continue to be areas of research emphasis. The Martian atmosphere provides some attenuation of the radiation, so the surface stay will be less harmful than the transit.

METHOD

For the analysis, coplanar injections were assumed, and a simple, massless-planet trajectory program was employed. This type of program is ideal for quickly determining trends in mission parameters. Since NASA is in the earliest planning stages for human Mars missions, the tool used does not have to be of high fidelity; it has to answer key questions in a short time so that common parameters can be established from which the geographically-diverse team can work. This simple method accomplishes that objective.

This paper will: (1) display the general trends for the variables in question, (2) show the implications of a trip time constraint, (3) illustrate the variation of entry speed across an injection window, (4) describe the aspects of designing stages for all opportunities, and (5) show the results of applying extra propulsion capability to reduce entry speed. Parameters for both the outbound (Earth-to-Mars) and inbound (Mars-to-Earth) trajectories were calculated. Throughout the remainder of this paper, data for both trajectories will be displayed; the data for the outbound trajectories will be discussed in detail. The trends of the variables are similar for both cases. In general, the Mars entry speed is of most concern, since the atmospheric environment is less known, and it is more difficult (or at least more expensive) to flight test a Mars entry than an Earth entry. Furthermore, although there are two Earth return options, the preferred human Mars mission architectures return the crew to Earth's surface directly, in a scaled-up Apollo capsule. This is a vehicle shape with a great deal of heritage, giving more confidence in its performance, although it will enter the Earth's atmosphere at a higher velocity than when it returned from the Moon (at about 11 km/sec.)

RESULTS

Trajectory Parameter Trends

Figure 2 shows the general trends for the departure energy and trip time for the Earth-to-Mars leg of the mission. Along the abscissa is the Earth year of the trans-Mars injection. Along the ordinate is the TMI energy requirement (C_3) in km^2/sec^2. C_3 is defined as the square of the V-infinity (V_{inf}) vector magnitude expressed in units of km/sec. C_3 is used in this study, rather than the more popular delta-V, since C_3 is independent of the parking orbit from which the vehicle departs. The various columns for each opportunity represent Earth-to-Mars transit times, in 10-day increments, from 180 to 210 days, with the last column in each group representing the minimum-energy Type I transit. The minimum-energy column is also labeled with the corresponding transit time. Note that the energy requirement generally increases with shorter trip times, over the range of trip times shown.

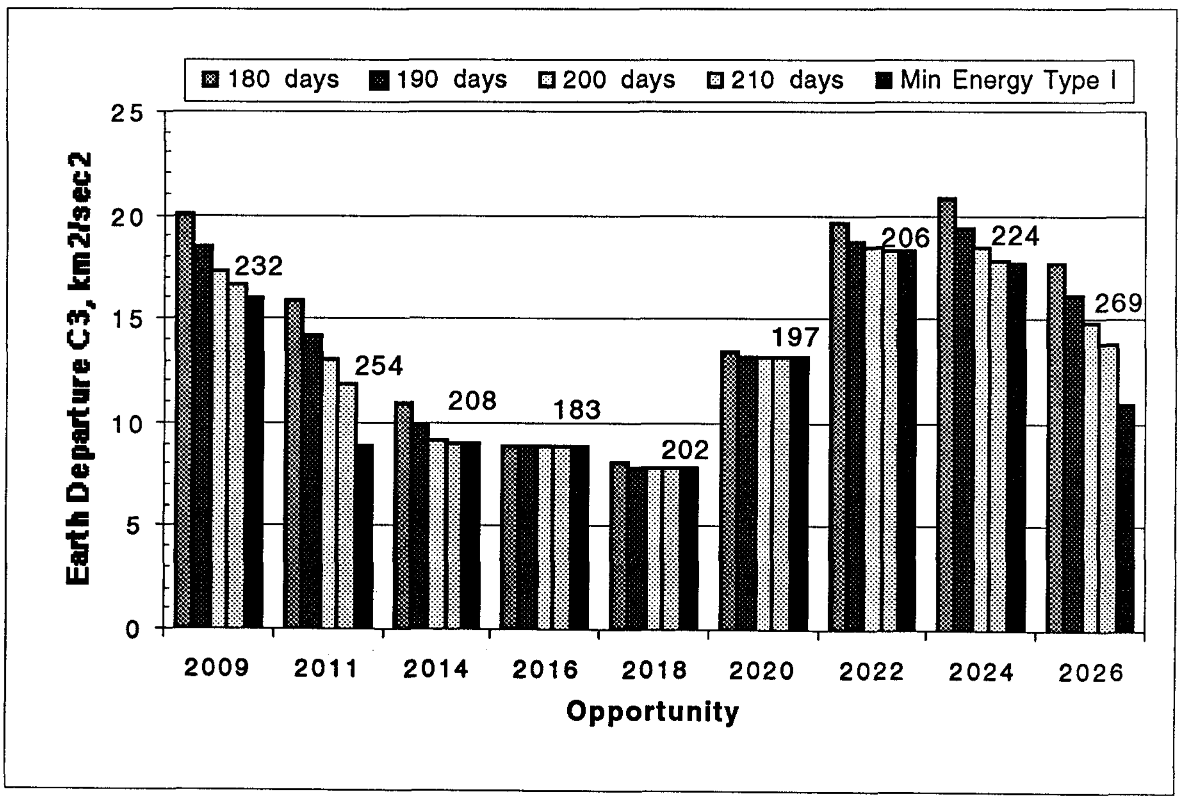

Figure 2 TMI Energies for Various Trip Times Across Mission Opportunities

Figure 2 also tells us something about performing missions in every opportunity. The graph shows that the most difficult opportunity, in terms of departure energy, is 2022. The minimum-energy trajectory in 2022, with a C_3 of 18.4 km^2/sec^2, takes 206 days. This means that if we want to utilize that opportunity using that energy level, we must relax our benchmark trip time of 180 days. One could argue that if the first human mission is in 2014, as is NASA's current plan, there will be adequate microgravity and radiation countermeasures by 2022 to accept this 26-day increase on the outbound leg of the mission. An alternate approach would be to design the TMI stage for the 180-day trajectory in 2022, which would require a performance capability of 19.8 km^2/sec^2. That was deemed excessive and was not the approach taken in this study, but it could become a valid approach if the extra trip time proved to be unmanageable.

Figure 3 is similar to figure 2, but shows the variation in Mars entry speed with trip time, for the outbound transfer. The entry speed is the Mars-relative velocity of the vehicle when it reaches the top of Mars' atmosphere, an altitude of 125 km. The entry speed generally increases with shorter transit times.

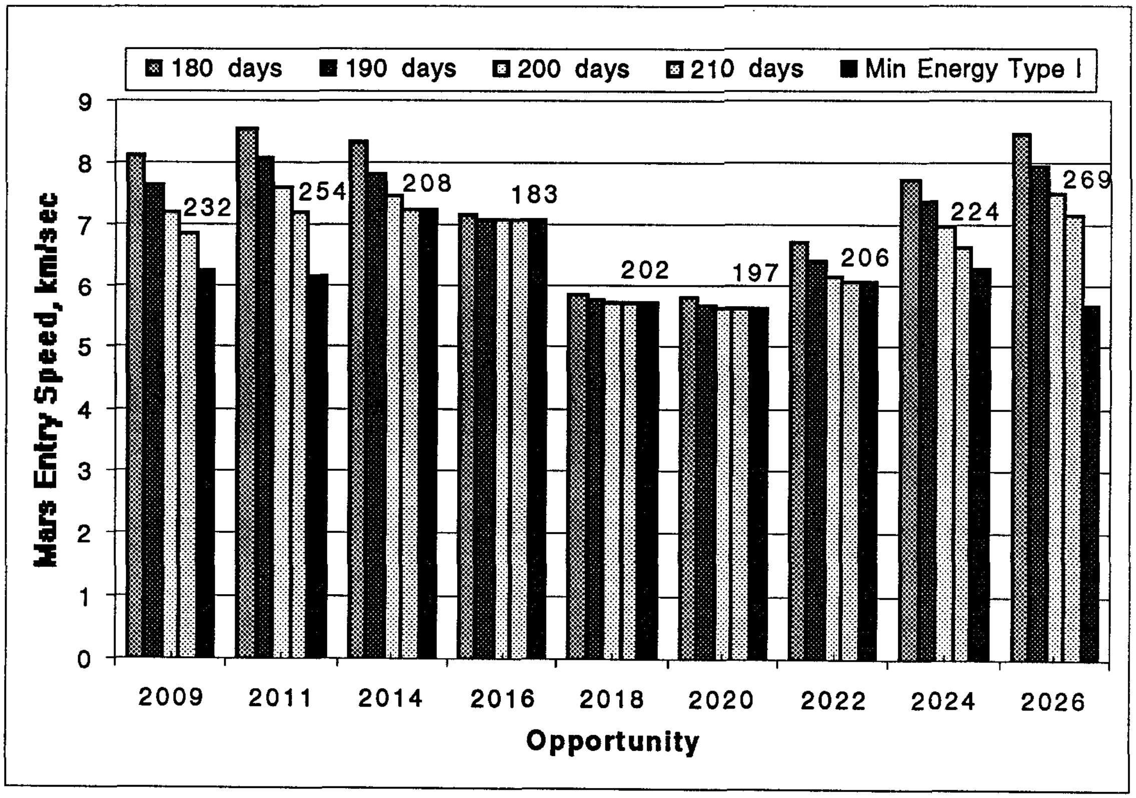

Figure 3 Mars Entry Speeds for Various Trip Times Across Mission Opportunities

Figures 4 and 5 are analogous to the previous two figures, for the trans-Earth injection maneuver and the Earth return. The ordinates are "Opportunity," so each cluster of columns represents returns from Mars during the specified Earth year opportunity (for example, the data labeled 2014 is the Earth return for a mission leaving Earth in 2014, even though it actually returns to Earth in 2016).

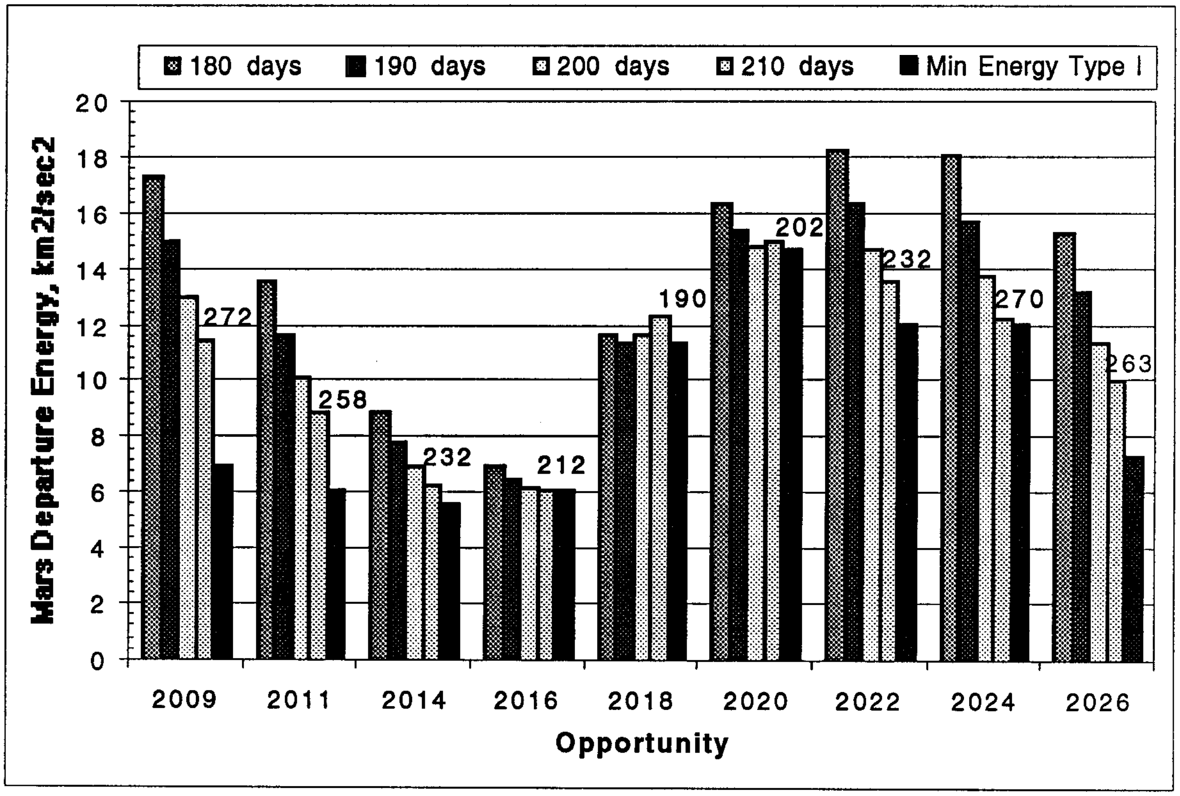

Figure 4 TEI Energies for Various Trip Times Across Mission Opportunities

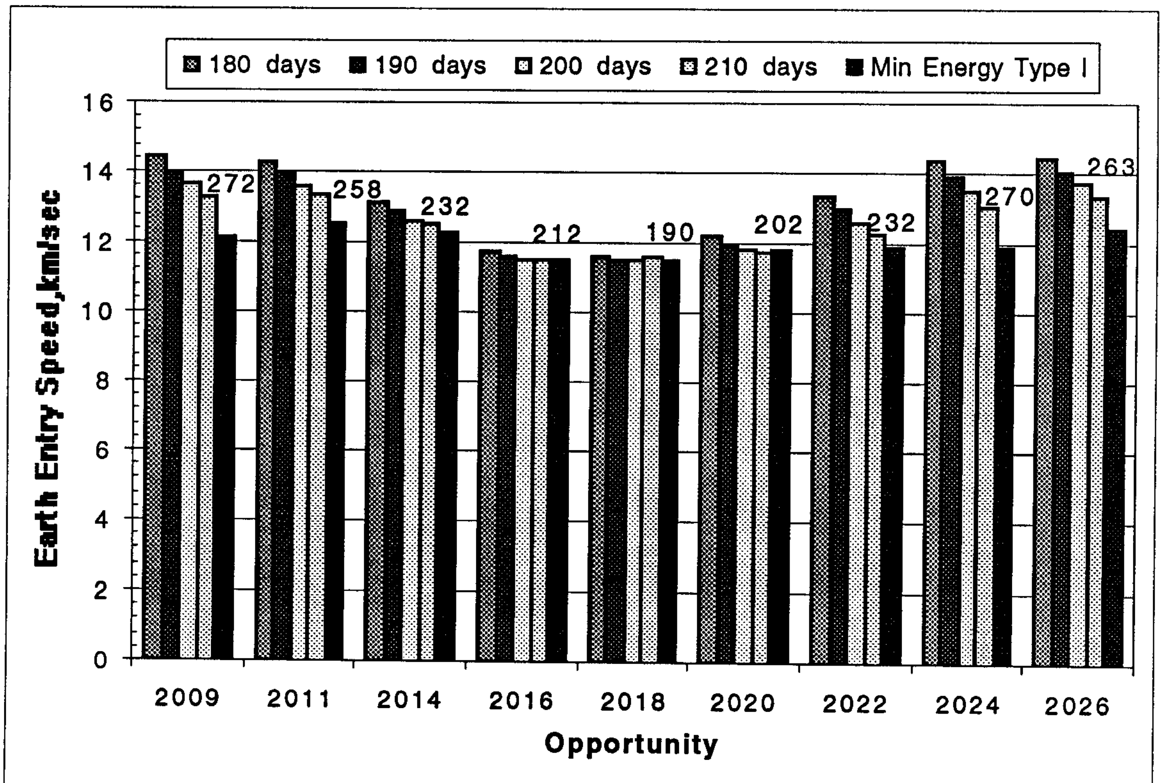

Figure 5 Earth Entry Speeds for Various Trip Times Across Mission Opportunities

In figure 5, the entry speed is calculated at 121.9 km above the Earth. The energy-defining opportunity for the return is 2020, when the minimum-energy Type I transfer requires a C_3 of 14.8 km^2/sec^2 and takes 200 days (again exceeding the 180-day constraint.) Notice that although the magnitudes of the energies and entry speeds are different, the trends are the same as for the outbound trip.

Figures 2 through 5 capture the problem at hand for human missions. To reduce energy requirements (i.e., propellant and therefore mass), longer transit times are better. To reduce entry speed (i.e., TPS development cost, and mass), longer transit times are better. To reduce negative effects on humans from zero-g and radiation, shorter transit times are better.

Constraining Trip Time to 180 Days

In order to perform comparison studies, mission designers choose one Earth-to-Mars and one Mars-to-Earth trajectory for each opportunity as the "nominal," from an architecture point of view. Since there is a benchmark trip time, transfer time is usually the most constrained variable. Table 1 lists the TMI and TEI C_3 values, trip times, and Mars and Earth entry speeds for trips less than or equal to 180 days. These represent the trajectories that have been chosen in previous studies to perform architecture-level sizing and packaging analyses. The 180-day transfer time is strictly obeyed, but the variable not constrained is entry speed. Note that using this approach leads to a TPS development to certify materials for 8.52 km/sec at Mars and 14.62 km/sec at Earth. Note also that if the injection stages are designed for every opportunity, with this trip time constraint, the required C_3 values are 20.8 km^2/sec^2 for TMI and 18.6 km^2/sec^2 for TEI. The philosophy used to size the injection stages needed for table 1 is to make them work for a cluster of opportunities; say 2014 to 2018, in the case of TMI. This approach has merits, in that it reduces some stage development cost, and allows new technology to be injected about every 6 years. In this study, a middle ground was used, that allowed common stages for all missions, but incurred less of a mass penalty than designing every mission for 180-day transfers, by lengthening the trip times in some opportunities.

Table 1
TRAJECTORIES CONSTRAINED TO 180 DAYS, FOR EACH OPPORTUNITY

Mission Year	TMI C_3 (km^2/sec^2)	Trip Time (days)	Mars Entry Speed (km/sec)	TEI C_3 (km^2/sec^2)	Trip Time (days)	Earth Entry Speed (km/sec)
2009	20.5	180	7.95	17.3	180	14.62
2011	16.0	180	8.50	13.8	180	14.14
2014	11.1	180	8.52	9.1	180	12.99
2016	10.2	160	8.44	8.6	160	12.23
2018	9.7	150	6.61	11.8	180	11.65
2020	13.5	180	5.86	16.5	180	12.36
2022	19.8	180	6.84	18.6	180	13.17
2024	20.8	180	7.89	18.2	180	14.11
2026	20.9	180	7.76	18.1	180	14.37
2028	17.8	180	8.48	15.3	180	14.48

Reducing Entry Speed

The next step is to take a closer look at how the planetary entry speed varies with departure energy for a particular trip time. We will examine 180-day transfers, since they represent the benchmark trip time. Figure 6 depicts a 50-day trans-Mars injection window with the minimum-energy departure date (the "nominal") nearly centered on the ordinate. Each of the points on the curves represents a trajectory that takes 180 days to reach Mars. If we move away from the minimum-energy departure date, keeping the transit time constant, the Earth departure energy requirement goes up, giving the "bowl" shape of the top curve. Within the same window, the later the Earth departure date, the slower the Mars entry speed. If the injection stages are designed for the most stringent opportunity, 2022, then there is extra energy capability in the "easier" opportunities. The minimum-energy trajectory that takes 180 days, for instance, would no longer have to be followed. The performance capability would exist in the propulsive stage to follow another 180-day transfer which results in a lower entry speed at Mars.

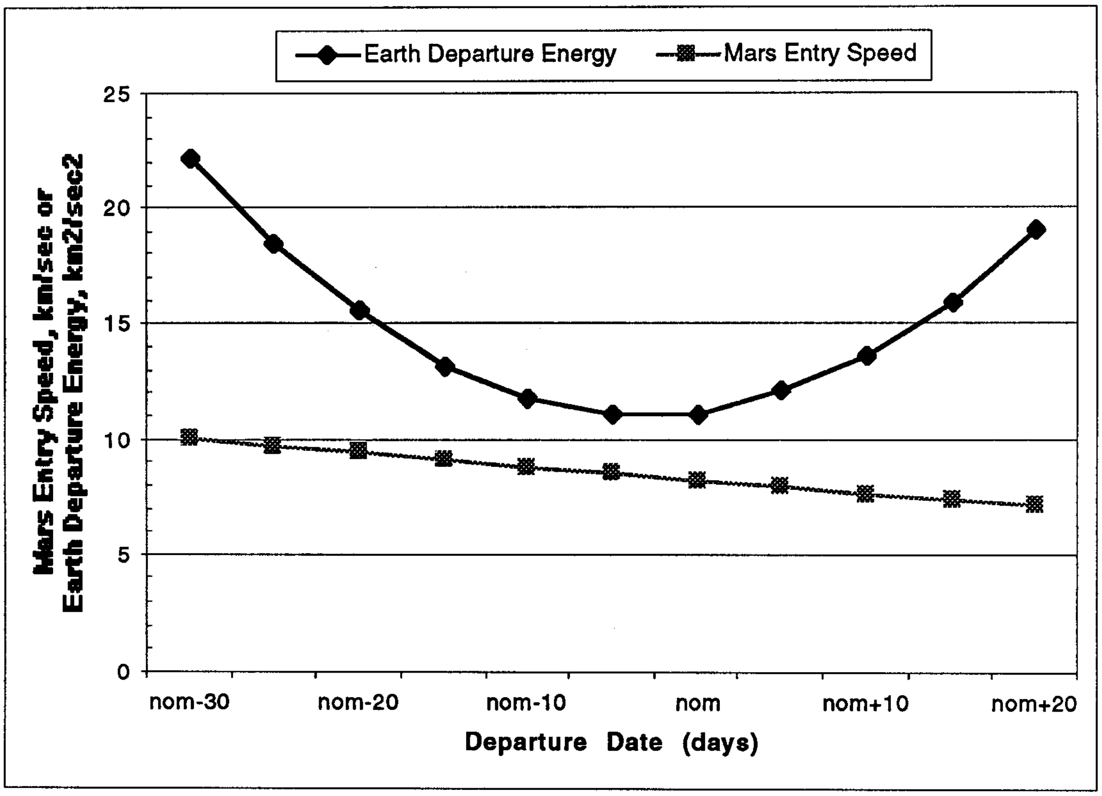

Figure 6 Earth Departure Energy and Mars Entry Speed Variations over 50 Days for 180-day Transfers in 2014

Figure 7 contains similar data for the return leg of the 2014 mission. The entry speed is slightly more sensitive to a 5-day change in injection date than in the outbound case. The figure illustrates that since the same trends exist on the Mars-to-Earth trajectory, the method of using any extra energy to reduce entry speed may be employed.

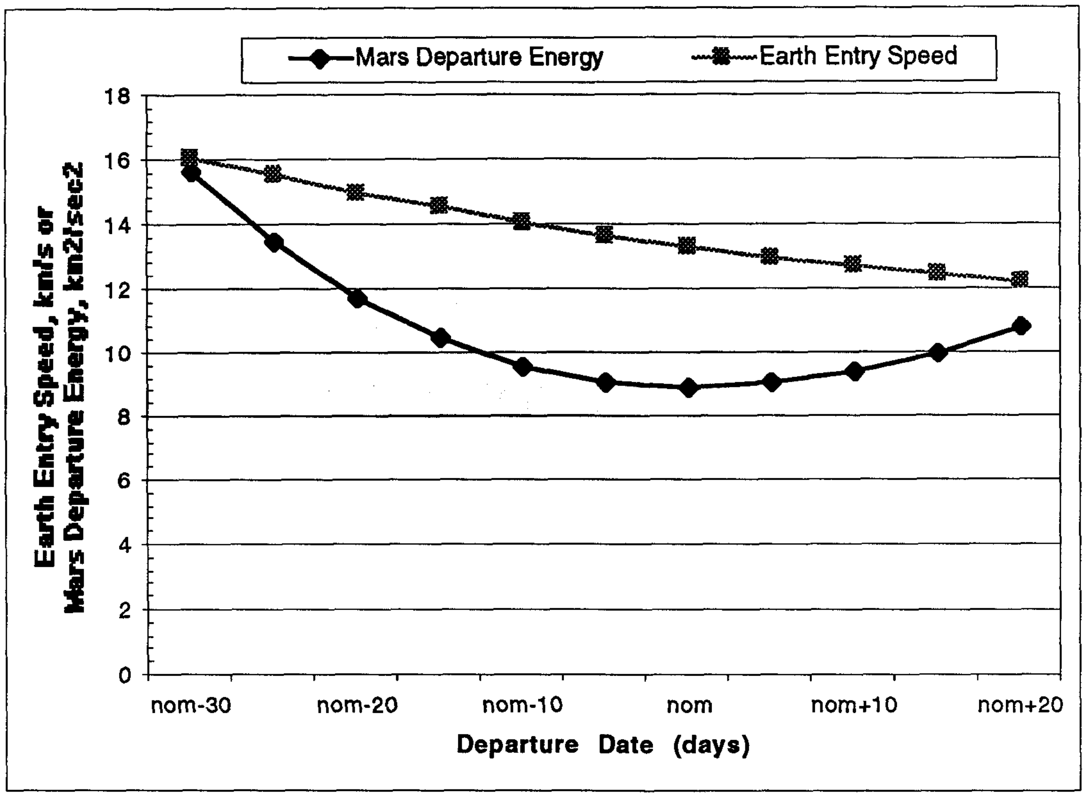

Figure 7 Mars Departure Energy and Earth Entry Speed Variations over 50 Days for 180-day Transfers in 2014

Trip Times Greater than 180 Days

Designing injection stages to perform in all opportunities results in energy requirements of 18.4 km^2/sec^2 for TMI and 14.8 km^2/sec^2 for TEI, driven by 2022 and 2020, respectively. As shown previously with figures 2 and 3, these levels of capability do not always allow transit times of 180 days; the transit time "violations" for the energy cycle 2011 through 2024, are listed in Table 2. Overall, we need up to a 26-day extension on some trips in later opportunities.

Table 2
TRIP TIMES GREATER THAN 180 DAYS DUE TO ENERGY CONSTRAINTS OF 18.4 AND 14.8 KM^2/SEC^2

Mission Year	Inbound/Outbound	Trip Time (days)
2022	Outbound	206
2024	Outbound	203
2020	Inbound	198
2022	Inbound	200
2024	Inbound	200

Using Energy to Reduce Entry Speed

Next, we apply the energy capabilities above to each opportunity to reduce the planetary entry speeds, while attempting to keep the remaining trip times equal to or less than 180 days. This approach gives the results in Table 3 for the outbound trip and Table 4 for the inbound. The cycle of interest is 2011 through 2024. For the outbound trip, in 2016 through 2020, the extra energy allows the trip times to be shortened to less than 160 days, while maintaining a reasonable entry speed.

Table 3
RESULTS OF MINIMIZING MARS ENTRY SPEED WITH AVAILABLE TMI ENERGY WHILE KEEPING TRIP TIMES CLOSE TO 180 DAYS

Mission Year	TMI C_3 (km^2/sec^2)	Trip Time (days)	Mars Entry Speed (km/sec)
2009	18.4	194	7.36
2011	18.0	192	7.34
2014	17.8	178	7.35
2016	18.0	154	7.09
2018	18.1	158	5.96
2020	18.0	153	6.15
2022	18.4	206	6.11
2024	18.2	203	6.95
2026	18.1	194	7.35
2028	17.9	186	7.30

The most difficult opportunity for both transfers is 2011, when the entry speed is very high in the region of the 180-day transfer. In that year, we must accept a trip time over 180 days, and use most of the C_3 available, to get entry speeds comparable to those in other years. It has been argued that the first human crew is not planned to leave for Mars until 2014, so we would not have to contend with this "difficult" opportunity. We must plan for it, however, because 2026 and 2028 present similar situations.

As shown by comparing tables 1 and 3, using this approach lowers the maximum Mars entry speed over the cycle from 8.52 km/sec to 7.36 km/sec. This will decrease the TPS mass and development cost. In addition, the entry speed has an effect on the width of the aerocapture corridor at Mars. Previous work has shown that the usable corridor can (depending on the vehicle and the trajectory constraints) increase from 0.39 degrees of flightpath angle to 0.87 degrees, when the Mars entry speed decreases from 8.52 to 7.36 km/sec; this decreases the risks associated with aerocapture.[2]

For the inbound trip, Table 4 shows that the entry speeds can be made about equal in all of the opportunities, utilizing the available TEI energy of 14.8 km^2/sec^2. This is another cost advantage, because all of the aeroshells can be manufactured alike. Using a maximum entry speed of 13.0 km/sec, the trip time can be reduced below 180 days in three of the opportunities. In the other 4 opportunities in the cycle, however, the trip time exceeds 180 days. This violation is caused in 2020, 2022, and 2024 by the available C_3, and only in 2011 by the desire to reduce entry speed. As discussed earlier, although we will probably not be returning humans from Mars in 2011, we will encounter this difficulty again on the 2026 mission's return.

Table 4
RESULTS OF MINIMIZING EARTH ENTRY SPEED WITH AVAILABLE TEI ENERGY WHILE KEEPING TRIP TIMES CLOSE TO 180 DAYS

Mission Year	TEI C_3 (km^2/sec^2)	Trip Time (days)	Earth Entry Speed (km/sec)
2009	14.7	199	12.97
2011	14.7	186	12.99
2014	14.8	156	12.97
2016	14.7	126	12.94
2018	14.8	150	12.01
2020	14.8	198	11.93
2022	14.8	200	12.63
2024	14.8	200	12.94
2026	14.8	193	12.96
2028	14.7	170	12.97

CONCLUSION

This study showed how three mission design variables can be manipulated for round-trip conjunction-class Mars missions. If the injection stages are designed to be adequate for any opportunity, they must have energy capabilities of 18.4 km^2/sec^2 for TMI and 14.8 km^2/sec^2 for TEI (with the simplifying assumptions of coplanar injections and no injection windows.) Designing common stages has two advantages. First, it reduces overall program costs, because the development is only done once, and the manufacturing methods remain constant. Second, the extra energy available in most years can be used to decrease the planetary entry speed, or shorten the trip time. Both of these improvements decrease mission risk. However, in 3 of 7 of the outbound opportunities in the energy cycle from 2011 through 2024, and 4 of 7 of the inbound opportunities, a 180-day transfer time is exceeded by at most 26 days, due to departure energy requirements. In 2011 only, the trip time extensions have to be made on both the outbound and inbound transfers to lower the entry speeds to values comparable to those in other opportunities.

Setting mission parameters such as maximum entry speeds, departure energies, and trip times, gives element designers requirements for their products and drives technology investment plans. As these studies continue and our experience in space grows, the challenge will be for the discipline experts to determine the real limits of these variables.

Future work will involve quantifying the mass penalty for using common injection stages, and the mass savings for using less TPS material on a slower planetary entry. Neither is expected to be a significant percentage of the total mass in low Earth orbit. There should be noticeable savings, however, in technology development, design, verification, and manufacturing costs for this new approach.

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